EF Report:
QCD, Detectors and Enabling methods

EF Meeting - Reports Reading and Discussion

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EF Reports in Snowmass wiki: https://snowmass21.org/energy/start#final_reports

QCD and Strong Interactions

- **QCD is a QFT that predicts a rich set of phenomena associated with both perturbative and non-perturbative dynamics of the strong interactions.**
- **Continued success of the HEP and NP research program hinges on an improved understanding of both regimes, as well as the dynamical transition between them**
  - Short-scale scattering processes
    → **perturbative QCD**
  - Long-distance processes
    → **non-perturbative QCD**
  - QCD in novel kinematic regimes
    → **forward and diffractive scattering**
  - Quark-gluon plasma and collective QCD
    → **heavy ion collisions**
  - New opportunities and tools
    → **cross-cutting QCD**

Current and Future Experiments

- **Upcoming era: HL-LHC, Belle II, the EIC**
  - A new golden age for QCD similar to the 1990's when the Tevatron, HERA, and LEP/SLD operated

❖ QCD radiative effects limiting factor in precision measurements (m_W, m_t boson and weak mixing angle) at hadron colliders

❖ Advances in theory, e.g. lattice QCD

❖ Jet, photon and top cross section measurements
  - ➢ Constrain pQCD, PDF and α_s running
  - ➢ Jet substructure for SM and BSM studies

❖ Far-Forward hadrons at Forward Facilities
  - ➢ Small-x, fwd heavy flavor prod., fragmentation

❖ DIS studies at EIC
  - ➢ Precision hadronic structure, proton PDF
  - ➢ Spin-dependent 3D tomography of nucleons and ions through highly-polarized beams
  - ➢ Theoretical and numerical tools at the interface between HEP and NP

- **Future Experiments:**
  - **1) e^+e^- colliders**
    - New techniques since LEP/SLD
    - Precise determination of α_s via event shapes
    - 2-jet-Higgs reconstruction: $H \to gg$ in $e^+e^- \to ZH$
  - **2) $\mu^+\mu^-$ colliders**
    - Pileup mitigation techniques developed for LHC will reduce impact of beam-induced background
  - **3) hh colliders**
    - Require innovative developments both in particle detection and QCD theory, e.g. EW bosons PDF, predictions for boosted final states inside jets, and new types of event generators
  - **4) MuIC, LHeC, FCC-eh colliders**
    - <1% measurements of α_s, nucleon structure, EW and Higgs couplings, as well as discovery machines to search for new physics (compositeness and leptoquarks)

Perturbative QCD

Les Houches wish-list

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$, $\mathrm{N^2LO^{(t)}_{QCD}}$, $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$	$\mathrm{N^4LO_{HTL}}$ (incl.), $\mathrm{N^2LO^{(b,c)}_{QCD}}$
$pp \to H+j$	$\mathrm{N^2LO_{HTL}}$, $\mathrm{NLO_{QCD}}$, $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{N^2LO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to H+2j$	$\mathrm{NLO_{HTL}} \otimes \mathrm{LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.), $\mathrm{N^2LO^{(VBF^*)}_{QCD}}$, $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{N^2LO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{N^2LO^{(VBF)}_{QCD}}$
$pp \to H+3j$	$\mathrm{NLO_{HTL}}$, $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VH$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{NLO^{(t,b)}_{gg\to HZ}}$	
$pp \to VH+j$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL}} \otimes \mathrm{NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to H+t\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{N^2LO_{QCD}}$ (off-diag.)	$\mathrm{N^2LO_{QCD}}$
$pp \to H+t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{N^2LO_{QCD}}$, $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to V$	$\mathrm{N^3LO_{QCD}}$, $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$, $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$, $\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$, $+\mathrm{NLO_{QCD}}$ (gg)	$\mathrm{NLO_{QCD}}$ (gg,massive loops)
$pp \to V+j$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$	hadronic decays
$pp \to V+2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$, $\mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{QCD}}$
$pp \to V+b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to VV'+1j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{QCD}}$
$pp \to VV'+2j$	$\mathrm{NLO_{QCD}}$ (QCD), $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW)	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^+W^+ +2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to W^+W^- +2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to W^+Z+2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to ZZ+2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$, $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^\pm W^+ W^-$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to \gamma\gamma$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma+j$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma\gamma+j$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$, $+\mathrm{NLO_{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	$\mathrm{N^2LO_{QCD}}$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to 2\,\mathrm{jets}$	$\mathrm{N^2LO_{QCD}}$, $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to 3\,\mathrm{jets}$	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to t\bar{t}$	$\mathrm{N^2LO_{QCD}}$ (w/ decays)+ $\mathrm{NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays, off-shell effects) $\mathrm{N^2LO_{QCD}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to t\bar{t}+j$	$\mathrm{NLO_{QCD}}$ (w/ decays, off-shell effects) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+2j$	$\mathrm{NLO_{QCD}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+Z$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD}}$ (w/ decays, off-shell effects)	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t\bar{t}+W$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays, off-shell effects)	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to t/\bar{t}$	$\mathrm{N^2LO_{QCD}}$*(w/ decays) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)
$pp \to tZj$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/ decays)	$\mathrm{N^2LO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays)

- **α_s uncertainty is a limiting factor in many measurements, e.g. Higgs couplings, at the HL-LHC**

Method	Relative $\alpha_s(m_Z)$ uncertainty: Current	Near (long-term) future
(1) Lattice	0.7%	$\approx$ 0.3% (0.1%)
(2) τ decays	1.6%	< 1.%
(3) $Q\bar{Q}$ bound states	3.3%	$\approx$ 1.5%
(4) DIS & PDF fits	1.7%	$\approx$ 1% (0.2%)
(5) e^+e^- jets & evt shapes	2.6%	$\approx$ 1.5% (< 1%)
(6) Electroweak fits	2.3%	($\approx$ 0.1%)
World average	0.8%	$\approx$ 0.4% (0.1%)

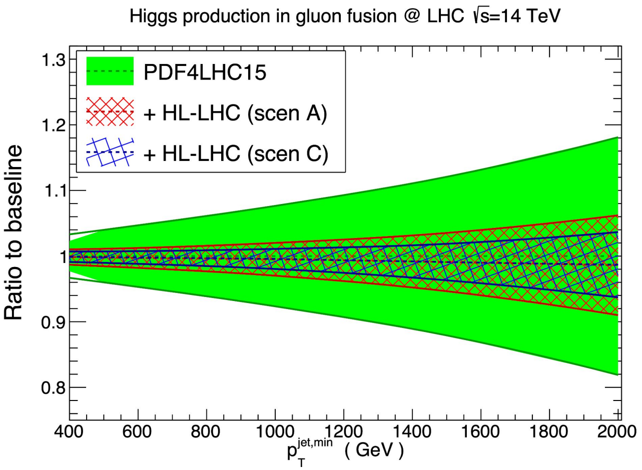
- **FCC-ee:** 3×10^{12} $Z\to qq$ at the Z pole, and $\sqrt{s}$ calibration 10's keV provides unparalleled α_s precision → searches for small deviations from SM predictions that could signal BSM
- **Jet substructure techniques:**
  - Identification of q/g-initiated jets in $l^+l^- \to H[\to gg]Z[\to ll]$
  - Identification of weak-strahlung emission, and $g\to tt$ in jets
  - Track functions in jet substructure

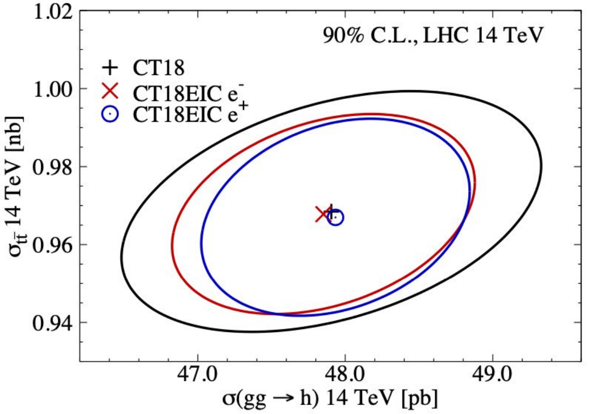
Non-Perturbative QCD

- PDF often dominant uncertainty in hh colliders,
- Also critical for BSM searches

Advances in PDF

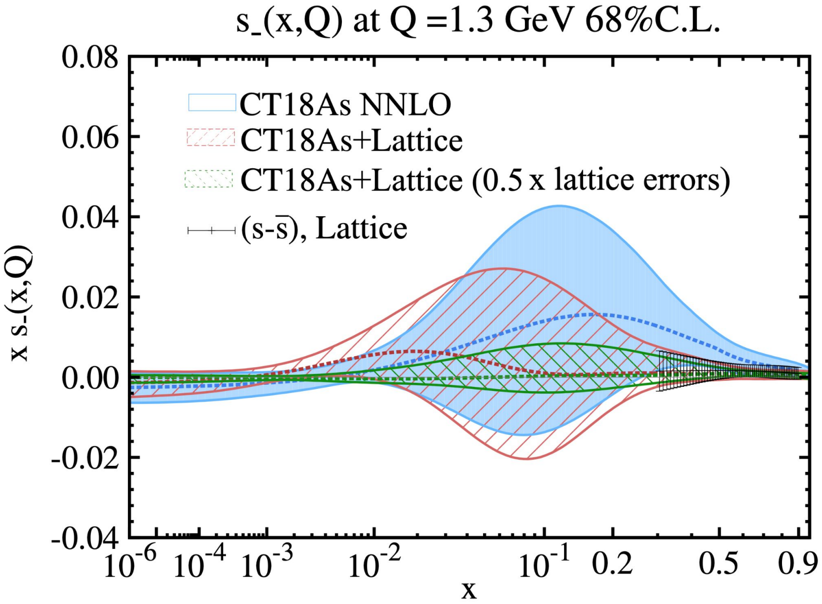
TOPIC	STATUS, Snowmass'2013	STATUS, Snowmass'2021
Achieved accuracy of PDFs	N2LO for evolution, DIS and vector boson production	N2LO for all key processes; N3LO for some processes
PDFs with NLO EW contributions	MSTW'04 QED, NNPDF2.3 QED	LuXQED and other photon PDFs from several groups; PDFs with leptons and massive bosons
PDFs with resummations	Small x (in progress)	Small-x and threshold resummations implemented in several PDF sets
Available LHC processes to determine nucleon PDFs	W/Z, single-incl. jet, high-p_T Z, $t\bar{t}$, $W+c$ production at 7 and 8 TeV	$+\ t\bar{t}$, single-top, dijet, $\gamma/W/Z$+jet, low-Q Drell Yan pairs, ... at 7, 8, 13 TeV
Current, planned & proposed experiments to probe PDFs	LHC Run-2 DIS: LHeC	LHC Run-3, HL-LHC DIS: EIC, LHeC, MuIC, ...
Benchmarking of PDFs for the LHC	PDF4LHC'2015 recommendation in preparation	PDF4LHC'21 recommendation issued
Precision analysis of specialized PDFs		Transverse-momentum dependent PDFs, nuclear, meson PDFs
NEW TASKS in the HL-LHC ERA		
Obtain complete N2LO and N3LO predictions for PDF-sensitive processes	Improve models for correlated systematic errors	Find ways to constrain large-x PDFs without relying on nuclear targets
Develop and benchmark fast N2LO interfaces	Estimate N2LO/N3LO theory uncertainties	New methods to combine PDF ensembles, estimate PDF uncertainties, deliver PDFs for applications





EIC will constrain the PDFs for the LHC high-mass BSM searches most directly, without systematic or new-physics factors relevant at the LHC

Non-Perturbative QCD

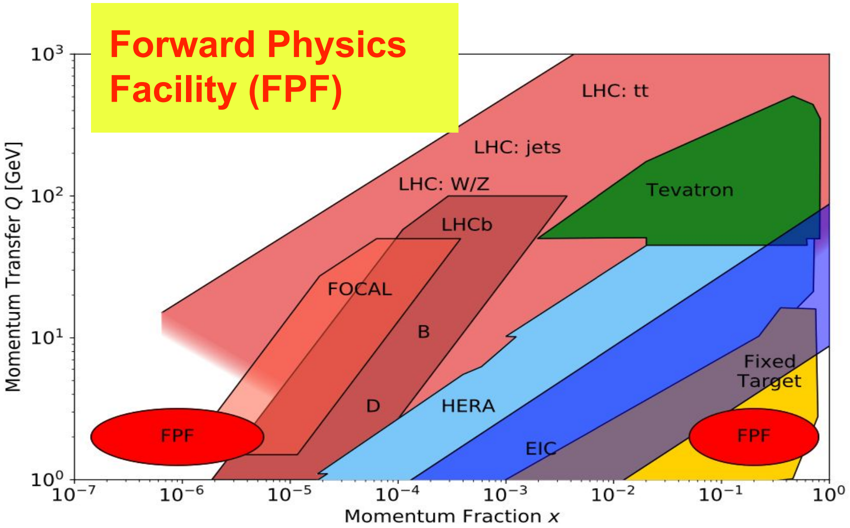


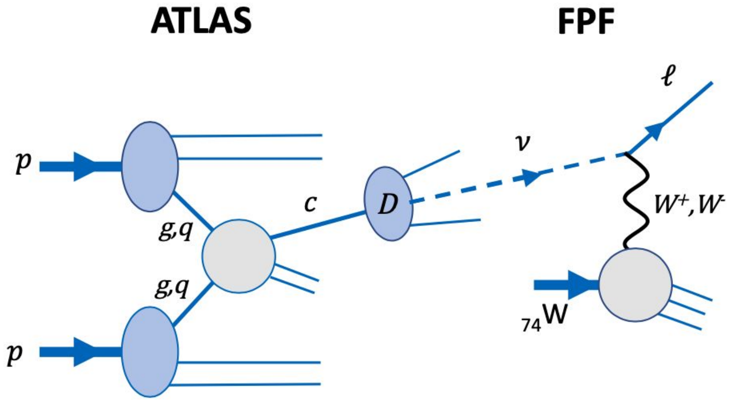
Future of PDF - Lattice

- **Rapid advances in lattice QCD**: PDFs and other QCD functions
  - Novel calculations can significantly constrain quantities difficult to assess with conventional PDFs
  - Computational resources are significant limitations on the achievable precision

- Hadronisation and Fragmentation Functions
  - Measurements planned at Belle-II, EIC and e^+e^- colliders

Forward Physics





- FPF will detect **far-forward neutrinos** from charm meson decays by DIS on a tungsten target
  - Improved predictions for key astroparticle physics processes, such as ultra-high energy neutrino-nucleus and cosmic ray interaction cross-sections
- **Neutrino–induced CC DIS** structure functions provide access to different quark flavor combinations compared to charged-lepton DIS
  - FPF will complement EIC
- PDF information, e.g. **high-x intrinsic charm**

- **Diffraction:**
  - Interesting to understand QCD dynamics, probing Odderon and Pomeron models, exploration of EW and BSM physics
  - Requires the combination of experimental measurements, e.g. EIC and FPF, and theoretical work
  - The FPF also allows exploration of BFKL evolution and gluon saturation

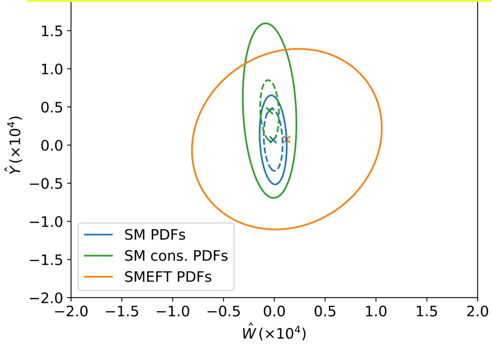
Heavy Ions

- **Quark-gluon Plasma:**
  - Hard Probes:
    - High momentum-transfer interactions between partons in the nuclei produce hard probes with QGP. Studies of the impact of QGP on color charges with fast-moving partons and slow-moving heavy quarks (jet quenching)
    - Thermalization of low-momentum heavy flavor quarks, which would then take part in the expansion and hadronization of the medium
    - Quarkonia can be dissociated in the medium due to Debye color screening or recombined from individual heavy quarks and anti-quarks diffusing through the medium
  - Hadronic structure:
    - Tetra-quarks, molecular states
    - Multi-charm baryons and new exotic states
  - Collective Phenomena:
    - Collectivity of small and large systems
- **EM interactions:**
  - UPC studies for both EM and nuclear interactions:
    - Vector mesons or jet production in photo-nuclear collisions
    - Light-by-light scattering

- HL-LHC experiments upgrades will benefit HI program
- cross-fertilization with RHIC experiments

Cross-Cutting QCD - Intersections of QCD and other domains

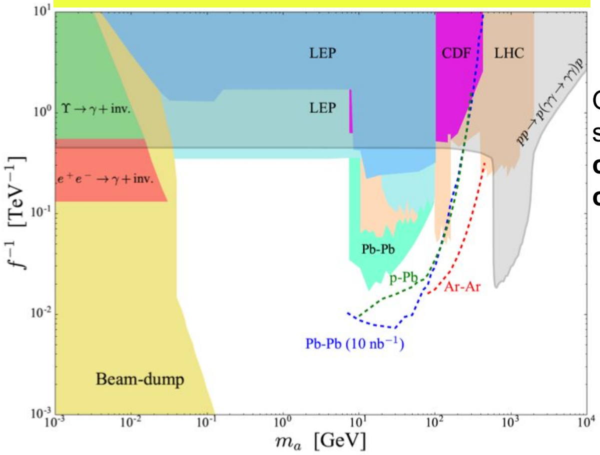
QCD in BSM searches (EFT fits)



Bounds on the respective Wilson coefficients are relaxed once they are fitted together with the PDF

- **Comprehensive uncertainty estimates**
  - **Collaboration between theorists and experimentalists**
    - consistent usage of QCD high-order calculations and conversion from parton to particle levels
    - support of QCD infrastructure that adapts theoretical tools for experimental analyses and provides protocols to validate these tools and assess uncertainties from experimental or theoretical sides.

EW and BSM physics in γγ scattering



Quantitative predictions for γγ scattering require **coordinated computations of QCD and EW contributions**

Hadron colliders offer unprecedented sensitivities to **quartic anomalous couplings** such as γγγγ, γγWW, γZZ, γγγZ, γγtt and **axion-like particles at high masses**

Enabling Technologies and Methods

Detectors

This section will be implemented soon.

It will be based on 2020 DOE Basic Research Need (BRN) Report and will discuss:

- Detectors for e^+e^- colliders (e.g. high granularity and low-mass)
    - Specific requirements for TeraZ detectors
- Detector requirements for hh and muon colliders (e.g. radiation hardness, fast timing)
- Detectors for auxiliary experiments, e.g. for LLP detection etc.
- Emerging technologies (e.g. 4D/5D, low-mass, monolithic etc.)

Monte Carlo Event Generators

Nearly all HEP experiments rely on the detailed modeling of multi-particle final states in MC simulations

- **Experimental uncertainties often dominated by effects associated with event simulation**
  - Underlying physics models and theory, truncation of perturbative expansions, parametrization or modeling of non-pert. QCD, tuning of model parameters, and fundamental parameters of the theory
- **Previously gained knowledge and experience can be transferred**
  - e.g. parton-to-hadron fragmentation can be similar for many facilities
- **Dedicated theory input to the simulation**
  - ***TeraZ:*** High-precision calculations - QED up to 4th and EW corrections up to 2nd order
  - ***Muon Collider:*** EW parton shower - EW effects to be treated on the same footing as QCD and QED
  - ***FPF:*** improved description of forward heavy flavor (charm) production, TeV-range neutrino scattering
  - ***EIC:*** Simulating spin-dependent interactions currently not possible at high precision with standard MCs and requires development of new tools at the interface between HEP and NP
  - ***Hadron Colliders:*** number of MC events that can be generated and computing efficiency play crucial role

Computational Resources

Experiments require computational resources in *design*, *operation*, and *data analysis* phases. Experiments must generate and simulate collision events and other backgrounds, reconstruct events, optimize their design, trigger on collisions, reconstruct events, calibrate the experiment, and analyze the reconstructed data

Expected computational resources in data

Collider Scenario	Event size	Event rate	Data/year
HL-LHC general purpose expt	4.4 MB	10 kHz	0.6 EB
FCC-ee Z-pole, one expt	1 MB	100 kHz	2 EB
CEPC 240 GeV, one expt	20 MB	2 Hz	260 PB
ILD 500 GeV	178 MB	5 Hz	14 PB
CLIC 3 TeV, 1 expt	88 MB	50 Hz	110 PB
Muon Collider, 1 expt	50 MB	2 kHz	2 EB
FCC-hh, 1 expt	50 MB	10 kHz	10 EB

- **MCs are the majority of offline compute and hot storage**
  - ATLAS projections for HL-LHC:
    - ≈ 70% of CPU and ≈ 60% of disk use from MC simul.
  - Proportion expected to be even higher for lepton colliders, (more democratic cross sections of relevant processes)

⇒ Efforts to optimize MC generators and detector simulation, use of computing accelerators, and ML approximations

- **Trigger farms** will still need to be located in physical proximity to experiments (latency requirements), but **offline processing** may take additional advantage of resources shared with other sciences (supercomputing centers) or provided by industry (cloud resources)
  - Choice influenced by the cost structure and technology availability then

Section to be developed further in XFrontier discussions at CSS with CompF and IF

AI/ML

AI/ML have come to pervade particle physics. Particle identification and event classification in data analysis and software triggering routinely use ML models.

Many still-unexplored possibilities for applying AI/ML with potential benefits in EF:

- **Anomaly detection** at data analysis or even trigger levels
- Transform ML models into FPGA code → deploying **ML in hardware triggers,** improving fast signal discrimination
- **Generative ML techniques to accelerate MC generators and simulation**
  - learn accurate approximations to a full physics model that can be executed much faster
  - increase the amount of MC events that can be produced with limited computing resources, improving the optimization of analyses and final statistical uncertainties
- **Detector design** is also an optimization problem
  - end-to-end optimization of a detector from scratch using target physics measurements
- ML models that respect important symmetries by construction and are potentially capable of being mapped onto first-principles theory → **acceleration for otherwise computationally-difficult problems, or rigorous interpretability**.
- **Tackling inverse problems**: determining regions of theory space that are compatible with observation

Challenges such as having the shortest possible time-to-insight on large amounts of data, and extracting small signals from large backgrounds, are not unique to HEP/EF ⇒ cross-fertilisation between different research fields and industry

Analysis Interpretation, Preservation and Open Data

This section will be implemented soon, referencing CompF7 (preservation) report, including the following:

- Importance of re-usable data and interoperable software
- Likelihood-sharing for combinations
- Reinterpretation of BSM searches using different models
- Data sharing for common summary plots (HEPData)